GULLY DYNAMICS: INITIATION AND MORPHOLOGY
(Keynote)

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1. Introduction

The paper reviews general conditions for initiation and maintenance of gullies.

Channel initiation is seen as a balance between infilling by diffusive processes and excavation by water-driven sediment transport. Where all material is coarse, and therefore governed by transport limited removal, then incision does not generally produce the sharp headcuts and deep incision associated with gullies. The concept of the effective bedload fraction (ebf), defined below, can be used to describe the proportion of the total sediment transport that is transport limited, and therefore acts as bedload that constrains the gully sediment budget. Where the ebf is small, gullies can cut channels at gradients less than those of the surrounding hillsides or fans into which they are cut, since they are able to remove most of the material eroded, allowing the development of characteristic sharp headcuts. Where the ebf is locally higher, for example where the gully cuts through a gravel lens, then gully gradient rises, and the depth of incision is reduced, in some cases preventing further headward extension of the gully.

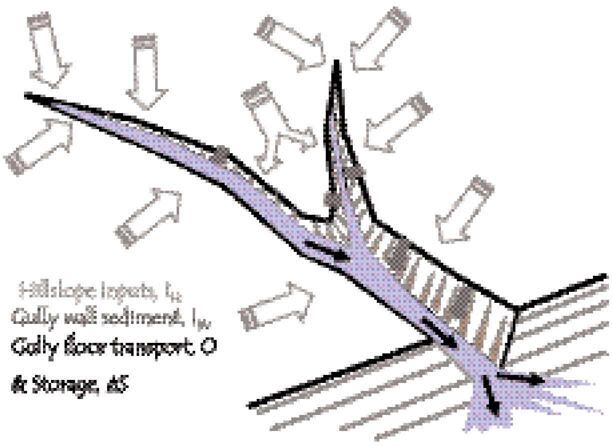

Fig. 1. Gully sediment balances: $I_H + I_W - O = \Delta S$. Sediment Delivery Ratio (SDR) = $O/(I_H+I_W) = 1/(1+\Delta S/O)$

Gullies can be initiated only where there is instability, in the sense of Smith and Bretherton (1972). For this to occur, any local incision will grow if and only if the additional flow converging on the incision is able to transport more than the additional sediment that is brought in, so that the local rate of incision exceeds the local rate of infilling. This Instability criterion can be expressed in the form:

$$\partial Q_S/\partial a > Q_S/a$$

where Q_S = sediment transport per unit width and a = area drained per unit width. In practice this criterion defines a critical distance or catchment area, beyond which fluvial transport can enlarge a proto-gully faster than rainsplash and rainwash can fill it in, coming back to Horton's (1945) critical x_c distance. However, it is also clear that this threshold distance varies from storm to storm, with smaller threshold distances in larger events, so that any current gully head position partly reflects the history of recent storms.

In addition, to form a gully, there must be accommodation space for removal of the eroded material, associated with available relief, commonly growing headward from a free face downstream/downslope; and a suitable material that can be transported by the processes active, usually sediment transport by overland flow.

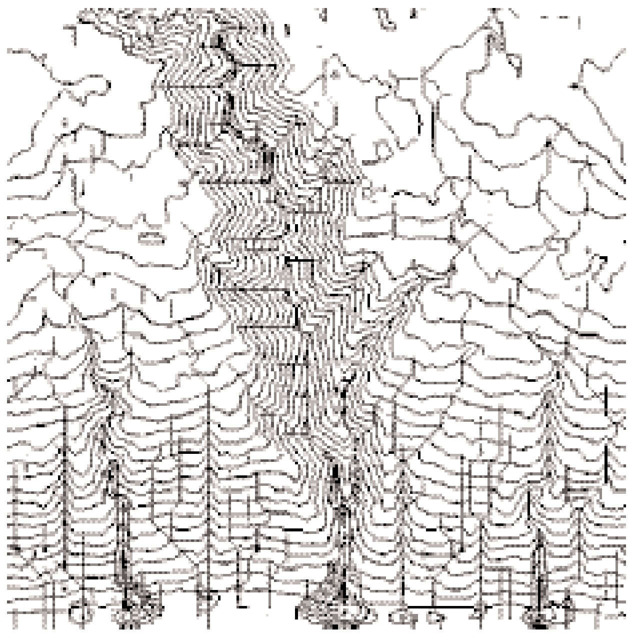

Fig. 2. Modelled gully evolution using the ebf concept (from Kirkby and Bull, 2000). Contours along bottom edge show fan deposition.

Actual sediment transport may be limited by the transporting processes, being carried at the transport capacity, and this is commonly the case for the coarsest fractions. Alternatively material may be limited by available supply, when transport is at much less than the transporting capacity, and this is commonly the case for the fines. These two concepts may be combined through defining the transport process through the two parameters of travel distance, h, and detachment rate, D. In a given flood flow, equal mobility suggests that

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the bed material is detached as a sheet, so that *D* is in proportion to the different size fractions present, but that *h* is roughly inversely proportional to grain size. The transporting capacity, *C*, for each grain size is then given by the product $C = D.h$, and can be compared with the composition of the source material, distinguishing the coarse transport-limited material from the finer supply-limited material, and so defining the (dynamically varying) effective bedload fraction. This concept is explored more fully in Kirkby & Bull, 2000., and used as a consistent basis for modelling gully evolution.

The stability criterion can then be approximately re-written as:

$$1/ebf.\ \partial C/\partial a > C/a$$

and this criterion becomes progressively less demanding for smaller ebf, allowing gullies to form closer to the divide, and with more pronounced headcuts (figure 2).

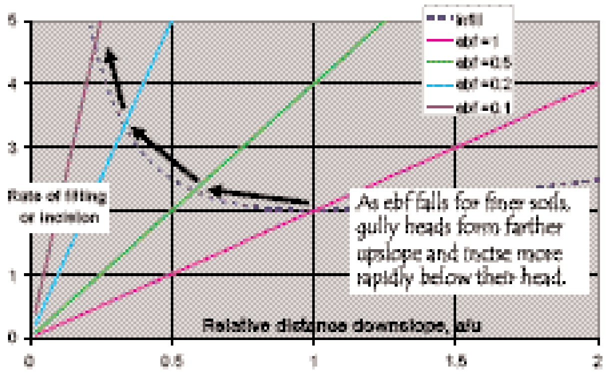

Fig. 3. Rates of initial gully enlargement for C ~ Ks. $(1+a^2/u^2)$ where s is gradient, and K, u are empirical parameters

In rough terms, the threshold grain size distinguishing bedload is usually in the range 1-5 mm, offering a rule of thumb for susceptibility to gullying.

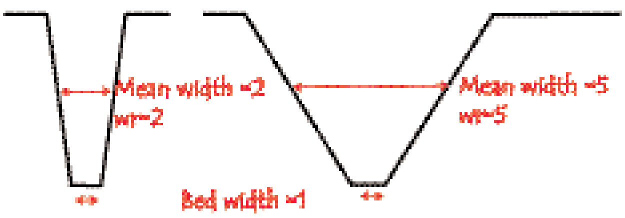

Fig. 4. Gullycross-section factors and the width ratio.

Away from the gully head, the contribution of sidewalls becomes increasingly important to the overall sediment budget, and incision is clearly limited where sidewalls have a low angle of stability. Where the ratio of average gully width to bed width is large, the much greater volumes removed during incision partially counteract the effect of a low ebf, and may prevent incision. At one extreme, the erosional feature takes the broad cross-sectional form associated with ‘ephemeral gullies’. It is suggested that the product of the ebf and the width ratio (wr) of mean gully width to gully channel width (Fig 4) provides an index of overall gully response, explaining some of the features of their distribution. Differences in substrate as a gully cuts down can also be important. In some environments, the surface layers are tougher than those below. This may be due to duricrusting and/or the accumulation of a lag deposit. The effect is to provide an initially high ebf, from the surface layer, but one that drops once the surface layer is breached, and erosion in predominantly in the finer material beneath. It may therefore require an exceptional storm to breach the surface layer initially, but then allow much more rapid subsequent incision.

In conclusion, it is argued that an understanding of gully dynamics has to be based on the hydraulics of flow and sediment transport and on a consideration of grain-size specific sediment budgets, taking into account material supplied at gully heads and from their sidewalls. From these considerations, it is argued that differences in the properties of the materials incised can help us to understand the spatial distribution of gullies and their morphology.

References

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of America*, 56, 275-370.

Kirkby, M.J. and L.J. Bull, 2000. Some factors controlling gully growth in fine grained sediments: A model applied to south-east Spain. *Catena*, 40 (2), 127-46

Smith, T.R. and Bretherton, F.P., 1972. Stability and the conservation of mass in drainage basin evolution. *Water Resources Research*, 8(6), 1506-29.